Offshore Steel Fish Farming Facility Integrated with Multi Vertical-axis Wind Turbines: A Conceptual Design and Hydrodynamic Analysis

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ABSTRACT--- The concept presented in this study is a combination of multiple megawatt (MW) vertical-axis wind turbines (VAWTs) with a floating steel fish-farming cage (MV-FSFFC). The design of this structure is described in detail, showing that a square shaped fishing cage accommodates four 3MW-VAWTs as the floating foundation. The hydrodynamic program WAMIT is employed to calculate the floater's motion response amplitude operators (RAOs) in sinusoidal waves of varying periods. The results show that the hydrodynamic performance of MV-FSFFC is better than OC3Hywind spar and OC4DeepCwind semisubmersible. The taut mooring system is adopted by this concept for stationkeeping. For 100-year design waves, the deterministic and stochastic extreme analyses of the mooring dynamic model for Stokes 5th-order wave and short term random waves are carried out. The whole structure exhibits outstanding hydrodynamic performances for its significantly small motions. Technically, MV-FSFFC owns strong competitiveness and wide prospects in offshore industry for both power exploitation and marine aquaculture in intermediate and deep waters.

Index Terms - Hydrodynamic response, fish-farming cage,vertical-axis wind turbine, stochastic waves.

I. INTRODUCTION

Offshore aquaculture and offshore wind industry are developing rapidly and they are concurrently moving into deeper and deeper waters, driven respectively by more severe coastal water pollution and richer wind resources in open seas. It seems that these two areas are irrelevant while an exception is that small wind turbines of hundreds of watts have long been employed by modest coastal fishing units to provide partial electricity power. The concept introduced in this study, however, is a combination of fishing facility with four multiple megawatt vertical-axis wind turbines (VAWT) for cultivation of fish and harness of wind power in an unprecedented large scale, with state-of-the-art technologies.

Due to their better economic benefits in onshore and near shore applications, recently the floating horizontal axis wind turbines (FHAWTs) has become a research focus in deep water power exploitation 1. Large commercial projects, such as the Kincardine and Buchan Deep projects in Scotland and the Fukushima Forwardproject 2 in Japan, have also driven the development of FHAWTs.It is worth mentioning that so far HAWTs have been employed from Western Europe to Eastern Asia, bottom fixed or floating. Nevertheless, there are two main drawbacks restricting further development of FHAWTs in deeper water sites. One is its heavy nacelle in the high altitude which not only demands costly marine operation but also causes unfavorable instability and structural resonance. The other is large distance mandated between two HAWTs that makes the wind farm less economical. By contrast, the floating VAWTs has several advantages, such as much lower gravity center, much lower noise, much lower installation and maintenance costs, lower cut-in wind speed, smaller rotational radius, smaller neighboring proximity, smaller cyclic load on the bearing, simpler power generation system. All these thereby are in favor of VAWT's bright prospect for the offshore power exploitation and have revived researchers' interests in VAWTs 3.

For decades, fish cages made of high density polyethylene (HDPE) have been widely used in lake, coastal, fjord fisheries for their light weights, low costs and easy fabrication 5. However, HPDE after all was proven to have poor mechanical properties (like low strength) to withstand an ocean storm. As a result, the life of a HDPE fishing cage in sea is usually less than 10 years and the effective fishing volume has reached its extreme at some $7500m^3$.However, since the success of Norwegian Ocean Farm fishing cage, steel material has quickly gained recognition by marine aquaculture.

In the present study, a novel concept that combines four multiple megawatt VAWTs with a steel fish-farming cage is introduced. It is designed to be unconditionally stable. The global motion RAOs for the floating substructure is investigated by the hydrodynamic potential program WAMIT 6. The seakeeping performances of this conceptual design are better than the currently popular substructures like OC3Hyind spar 7 and OC4DeepCwind semisubmersible wind turbines 8. In the situation of taut mooring, the deterministic and stochastic extreme dynamic responses respectively subjected to Stokes-5th-order wave

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and short-term random waves are also studied for 100-year waves. The induced heave motion is less than 3.5*m*. When one taut mooring line is broken, the maximum heave motion approaches 5*m*. Due to its large dimensions of fishing cage, especially its deep draft, the effective contained water volume is as large as 290,000m^3, fairly comparable to that of Ocean Farm. Thus, the pay-back period for the investment is less than 3 years due to considerable revenues from both power generation and fishing. From the seakeeping, structural dynamic and rate-of-return views, the MV-FSFFC is a very competitive candidate in offshore power and fish farming industries.

II. CONCEPT DESIGN OF THE MW-FSFFC

The whole structure of the MW-FSFFC comprises four main parts: (1) a square-shaped steel fishing cage; (2) four multi-megawatt VAWTs sitting on the corner columns of the cage; (3) taut mooring systems (4) a living quarter for personnel accommodation, as shown in Fig. 1.

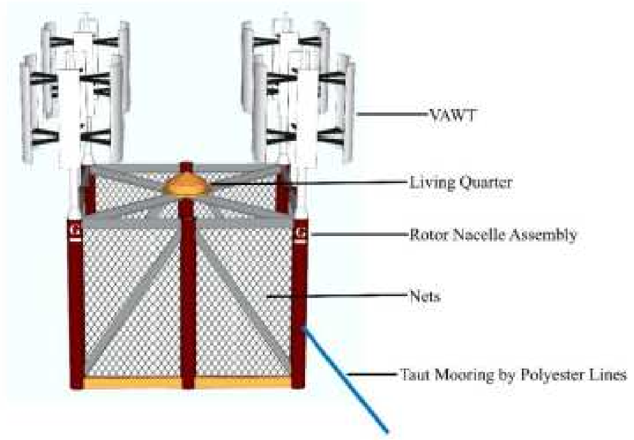


Fig. 1 Configuration of the concept of MW-FSFF

A. Floating fishing cage

Water depth at the operation site is one of most important factors affecting the choice of floating structure type. This concept assumes that the water depth is about 100-150*m*, a very probable depth that the humankind will conquer by the year of 2030 for marine aquaculture. Due to its excellent stability in water, the spar concept is adopted in the design of MW-FSFFC to accommodate VAWTs. As illustrated in Fig.1, the floating foundation of MW-FSFFC is a square-shaped steel fishing cage whose center of gravity (CG) is significantly lower than its center of buoyancy (CB).

This floating structure consists of 12 pontoons (8 sided and 4 crossings) in the bottom frame, 9 vertical columns (including the central column), and 16 braces (8 sided and 12 in the top frame). The configurations are given in Fig.2. The cross sections of pontoons are rectangular,while all other structural members are circular cylinders for convenient construction. Table 1 lists the details of sections. The steel fishing cage is 96m wide and 50*m* tall. The effective draught for normal operation is 40*m*, leaving 10*m* for the airgap beneath living quarter to prevent underdeck wave slamming. Table 2 gives the mass break-down for key structural members of the fishing cage and their CGs.

The material of all fishing nets is copper alloy which is able to resist corrosion and biofouling. It is worth noting that in order to lower CG of MV-FSFFC a large volume of ballast using high-density concrete is placed inside the bottom pontoons.

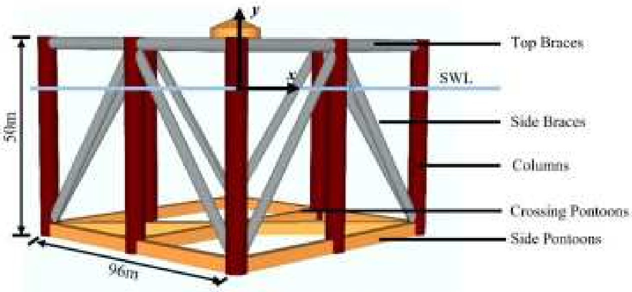


Fig.2 Side view of the fishing cage

Table 1 Dimensions of key members in the fishing-cage

Member	Section(m)	Number	Length (m)	Thickness(m)
Side Pontoon	□ BxH=2x2	8	45.0	0.030
Crossing Pontoon	□ BxH=2x2	4	63.6	0.030
Column	○ D=6	9	50.0	0.033
Side Brace	○ D=2	8	67.2	0.020
Top side Brace	○ D=2	8	45	0.020
Top Crossing Brace	○ D=2	4	63.6	0.020

Table 2 Mass break-down

Component	Mass (t)	CG (m)
Steel Structure (excludingpontoon)	3958.9	-10.1
Pontoon (including concrete ballast)	10209.0	-39.0
Living Quarter	200.0	10.0
Copper Alloy Nets	140.1	-23.2
Rotor Nacelle Assembly	1200.0	8.0
Total	15708	-27.4

Note: CG is measured from SWL (Fig. 2)

B. Wind turbine and tower

The distance requirement between two neighboring VAWTs is remarkably smaller than that between HAWTs.This allows VAWTs to be grouped onto a floater to improve the efficiency of wind farm. In MW-FSFFC, four 3-MWVAWTs sits on the corner column of the steel fishing cage, such that the net distance between neighboring VAWTs could exceed 25m assuming that the blade rotational diameter reaches 70m without compromising the power efficient. This study also assumes that the rotor nacelle of each VAWTweights 300*t*and is placed in the hollow space of corner columns to lower the center of gravity. In this sense, the height of the wind turbine tower is no longer a critical condition affecting the performance of structural stability. Details of turbine wings and nacelle are not included, since this study focuses on the performance of substructure.

C. Taut mooring system

The taut mooring is adopted in this concept to maintain small stationkeeping motions. Fairleads located at the corner columns are 22m below the SWL. For convenience, the dynamic modulus *AE* can be expressed as

$$AE=RHOL(\alpha+\beta\frac{T}{B_s}) \qquad (MN) \tag{1}$$

Where $B_s$is minimum breaking strength (MBL), T is time-dependent tension, and *RHOL* is dry weight per unit length of the polyester. In this study, α=4.8 and β=0 are used 9 to have a constant *AE*. The material properties of the polyester fiber are tabulated in Table 3. The top view of the mooring line layout is shown in Fig.3.

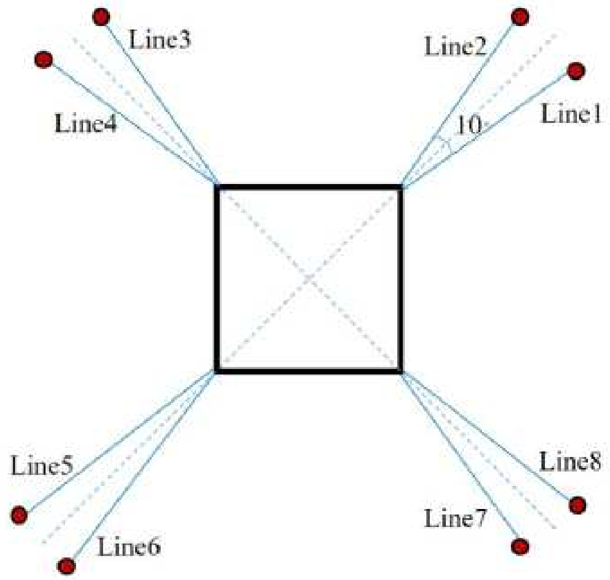


Fig.3 Mooring line layout (top view)

III. HYDROSTATIC ANALYSIS

The hydrostatic parameters of the MV-FSFFC system at static equilibrium position are listed in Table 4. Y_{GC} and Y_{BC} represent Y-coordinates of CG and CB of the system (excluding the mooring lines), respectively. There difference is about 6 meters. CG is always lower than CB, ensuring that MV-FSFFC is unconditionally stable like a floating spar-type structure.

In calm water, the largest deformation could occur at top braces (Fig. 2). The software ABAQUS10 is employed to carry out static finite element analysis (FEA) considering gravitational and buoyancy forces. Fig. 4 and 5 illustrate the deformation and stress distribution of the top frame. The largest deformation of 33mm occurs at the top crossing braces, though no buckling appears. FEA also shows that for all structural members of MV-FSFFC, the longest natural period of free vibration is less than 1*s*. Hence, no resonance would be triggered by ocean waves on members. It is however of more interest and importance to look into the hydrodynamic performance of the overall MV-FSFFC as a rigid floating body.

IV. HYDRODYNAMIC ANALYSIS: FREELY FLOATING

In hydrodynamic analysis of a floater, the response amplitude operators (RAO) of motions reflect the seakeeping performance in waves. In this study, the motion RAOs of the MV-FSFFC are obtained using the frequency-domain potential flow program WAMIT which treats the substructure of MV-FSFFC as a rigid body with six degrees-of-freedoms (DOFs), ξ_j (j=1,2…,6). They are surge, sway, heave, roll, pitch and yaw, calculated by the flowing governing equation.

$$\sum_{j=1}^{6}\Big[-\omega^2\left(M_{ij}+M_{ij}^E+A_{ij}\right)+ i\omega\left(B_{ij}+B_{i,j}^E\right)+\left(C_{ij}+C_{ij}^E\right)\Big]\xi_j=X_i \tag{2}$$

where M_{ij} is inertia matrix of MV-FSFFC; M_{ij}^E is external mass matrix; $A_{ij}$is the added mass matrix; B_{ij} is added damping matrix; B_{ij}^E is external damping matrix; C_{ij} is hydrostatic restoring matrix of MV-FSFFC and C_{ij}^E is external stiffness matrix. These matrices are in 6x6 dimensions. X_j is a 6x1 load vector induced by linear regular waves taking into diffraction effect.

Table 3 Main property of mooring line

Designation	Unit	Quantity
Pretension	kN	1200
Number of Lines		8
Length of Mooring lines	m	128.12
Fairlead Location from SWL	m	-22
Length	m	118.12
Diameter	mm	140
Dry Weight (RHOL)	kg/m	14.58
Wet Weight	kg/m	3.40
Stiffness AE	MN	70
Minimum Breaking Load (MBL)	MN	6.51

Table 4 Hydrostatic parameters in static equilibrium position

Designation	Unit	Quantity
Displaced Volume	m^3	15324
Waterplane Area	m^2	279.4
Operating Water Depth	m	100
Y_{GC}	m	-21.6
Y_{BC}	m	-27.4

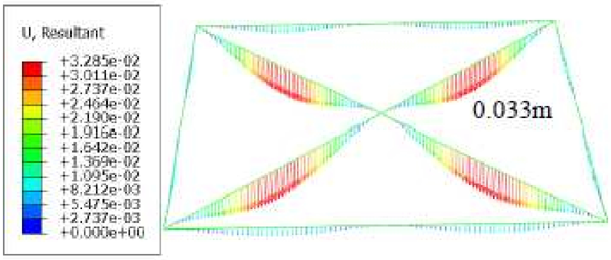


Fig.4Deflection of top braces

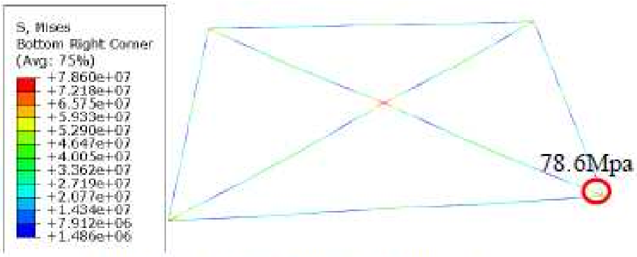


Fig.5 Stress distribution of top braces

Damping significantly affects motion RAOs. Slender structural members and the copper alloy nets in the steel fishing-cage lead to non-negligible viscous drag damping. In this study, the total damping element in matrix can be obtained by the following

$$c = 2\varsigma m\omega \qquad (3)$$

where ς is damping ratio, and 0.03 is adopted in the study; m is mass; ω is natural frequency corresponding to each DOF of motions.

Fig. 6 and 7 compare the heave and pitch RAOs of the MV-FSFFC with the well-known OC3Hywind and OC4DeepCwind floaters in head seas (wave heading angle of 0°). Fig. 6 shows that the heave RAO of MV-FSFFC is the smallest among all three floaters in the wave period range of 5-13.5*s*. The peak heave RAO of MV-FSFFC is 2.4m, also smaller than the other two floaters. As for peak pitch RAO of MV-FSFFC, it is only a half of the OC3Hywind and almost a third of the OC4DeepCwing. The peak pitch RAO occurs at wave period of 20.4s which is far beyond the period of wind-generated waves in most of seas. It is therefore concluded that MV-FSFFC has very good seakeeping performance.

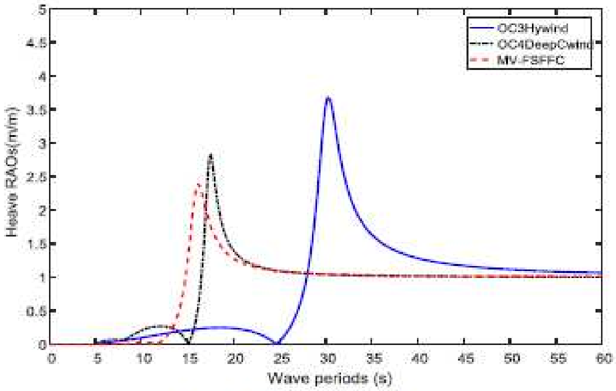


Fig. 6Heave RAOs in head seas(0°)

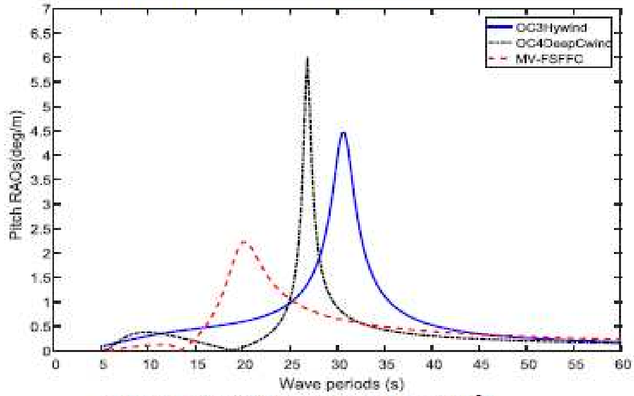


Fig.7 Pitch RAOs in head seas (0°)

V. HYDRODYNAMIC ANALYSIS: TAUT MOORING

A. Modeling and environmental conditions

MV-FSFFC is moored by eight polyester lines, as shown in Fig.3. The three dimensional modelling with taut polyester mooring lines is created using software OcraFlex 11 to carry out coupled analysis in the time domain. The JONSWAP wave spectrum is used for short-term stochastic analysis. The design wave for the survival condition is Hs=7*m*, Tp=12*s*. Based on the Rayleigh assumption, the mean extreme wave height H_{max} and the corresponding T_{max} in a 6-hour storm are obtained to formulate an equivalent Stokes-5th order wave in the deterministic analysis. The environmental conditions are summarized in Table 5.

B. Motion RAOs with mooring system

If the input waves are white noise, the motion RAOs can be easily derived from the time history generated by OcraFlex. The time history of heave motion under a white noise excitation (head seas) is shown in Fig. 8.The corresponding RAOs is shown in Fig.9. It is noticeable that theheave RAO response is smaller under taut mooring system. Since the eight taut lines increase the overall structural stiffness, the natural period of motions is shortened from 17.7*s* to 12*s*.

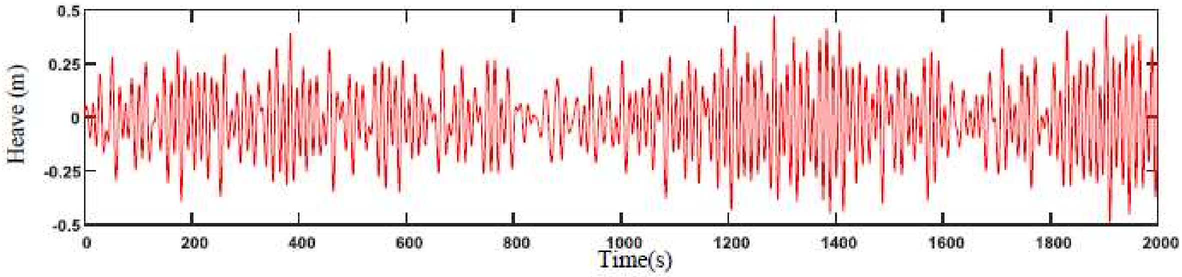


Fig. 8 Time history curve of heave response in head seas (wave angle of 0°)

C. Hydrodynamic analysis for intact condition

MV-FSFFC is designed to survive storms of Beaufort scale of 10 that are frequently encountered in Asian waters. The selected ocean wave conditions representing the 100-year design wave are summarized in Table 5. For short term stochastic analysis,the maximum tension (3.66*MN*) occurs in the wave attack direction of 30°. Therefore, in this wave direction random time histories of heave and pitch responses as well as the mooring line tension are compared with the results driven by deterministic Stokes 5th-order wave (Fig. 10). The results show that the maximum dynamic response subjected to Stokes 5th-order wave approaches to a steady value that is much smaller than the stochastic response, since the regular wave period of 10.8*s* is slightly shorter than the peak heave period in RAOs (Fig. 9). For the heave motion, the maximum response is 3.34*m* under stochastic wave, whereas the value is only 0.65*m* under deterministic wave. Though deterministic pitch response is quite comparable to stochastic pitch response within the simulation duration, the maximum pitch response (4.5 degrees) driven by the stochastic ocean waves is still outstanding at t=1680*s*. For the mooring line tension, the stochastic results are significantly larger than the deterministic results. It is concluded that the stochastic analysis cannot be replaced by the commonly used deterministic analysis. Fully coupled stochastic analysis in the time-domain is very necessary for a newly developed concept.

Table 6 summarizes the statistics of stochastic tension of mooring lines. According to the limiting values specified by the API-RP 2SK provisions 13, safety factors should be larger than 1.67 for structures with intact mooring system. The smallest safety factor listed in Table 6 is 1.77, implying that all mooring lines are able to survive the design waves in Table 5.

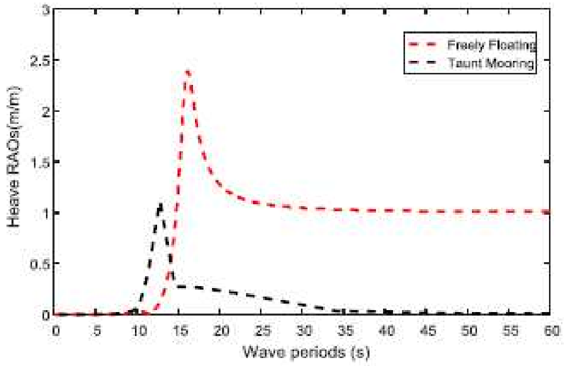
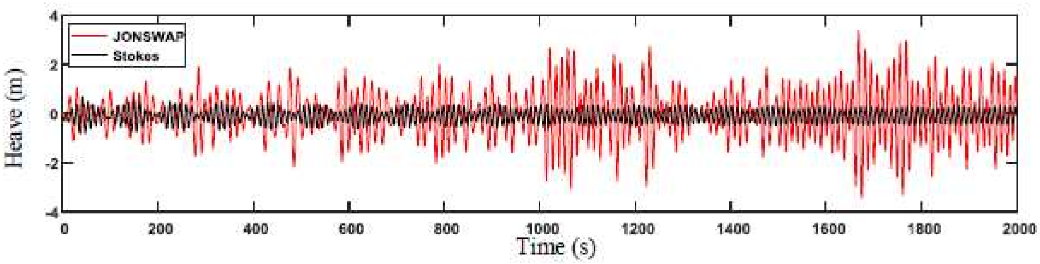


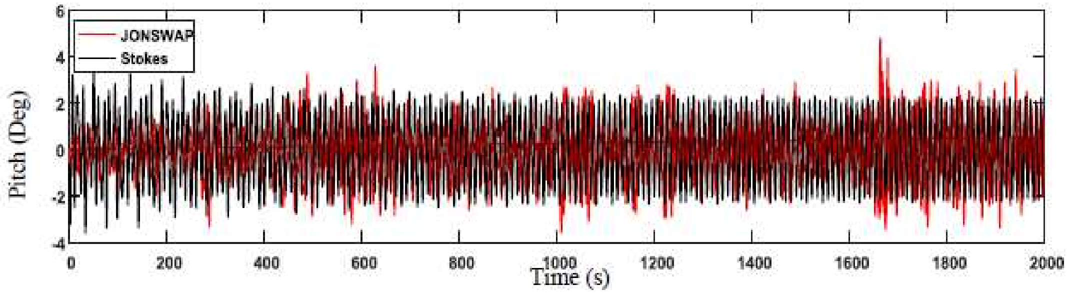
Fig.9 Heave RAOs in head seas (0°)

Table 5 Design wave conditions

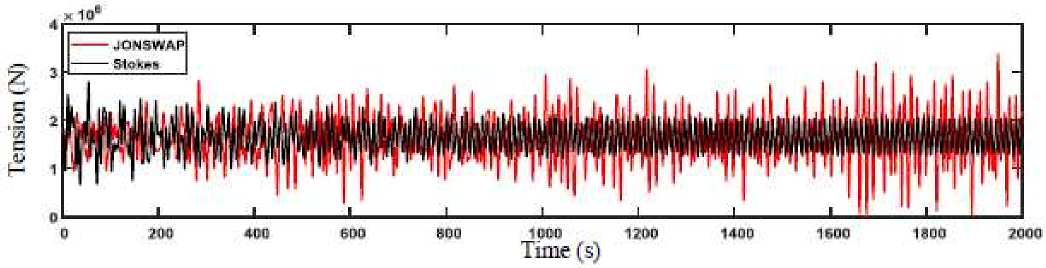
	Unit	Value
Seawater density	kg/m^3	1025
Stochastic Wave		
Significant wave height (H_s)	m	7.0
Peak wave period (T_p)	s	12.0
Wave spectrum	JONSWAP (γ=1.71)	
Wave directions	degree	0/35/45
Duration time	hour	6
Deterministic wave		
H_{max}	m	14.3
T_{max}	s	10.8
Wave type	Stokes 5th-order wave	



(a) Heave response



(b) Pitch response



(c) Tension response of mooring line #1

Fig. 10 Comparison of stochastic and deterministic analyses for the intact condition (wave angle of 30°)

D. Hydrodynamic analysis for one line-broken condition

In case that one of the eight mooring lines fails after long-term fatigue action or in an accidental event, it is necessary to look into the safety redundancy of the mooring system and the hydrodynamic response of MV-FSFFC. Based on the provisions in API-RP 2SK 13, the No. 1 mooring line that has the maximum tension is removed for the broken condition analysis. The stochastic wave represented by the JONSWAP spectrum is selected as the wave input (Table 5). The results in Table 7 show that removal of a mooring line greatly increases the force on the remaining seven lines. The increase of maximum force for Line 2 is 32% and the corresponding safety factor is 1.35 that still meets the requirement of 1.25 for the line-broken condition in API-RP 2SK.

Table 6 Statistics of tension in mooring lines (wave angle of 30°)

Line Number	Maximum (kN)	Minimum (kN)	Mean (kN)	Std. deviation (kN)	Safety factor
1	3.66E3	1.28E2	1.66E3	4.86E2	1.77
3	3.17E3	1.73	1.65E3	4.47E2	2.05
5	3.27E3	7.67	1.62E3	4.81E2	1.88
7	3.59E3	2.15E2	1.61E3	4.59E2	1.81

Table 7 Statistics of tension in mooring lines (wave angle of 30°)

Line Number	Maximum (kN)	Minimum (kN)	Mean (kN)	Std. deviation (kN)	Safety factor
2	4.83E3	1.78E2	2.31E3	7.18E2	1.35
3	3.94E3	73.11	1.84E3	5.57E2	1.65
5	3.21E3	1.43	1.22E3	5.38E2	2.02
7	3.68E3	2.38	1.61E3	5.93E2	1.77

VI. CONCLUSION

A new concept that integrates the fishing facility with multiple megawatt VAWTs is presented in this study. The hydrostatic and hydrodynamic analyses of the proposed MV-FSFFC concept are carried out. The following conclusions can be drawn.

1) The MV-FSFFCis a multifunctional floater. Its substructure is a large steel fishing cage which also serves as the foundation of four vertical wind turbines. Such design not only makes good use of the space of wind farm, but also helps to rapidly shorten the payback period of heavy investment in wind turbines, due to vast fishing production.
2) The MV-FSFFC has excellent hydrostatic stability, since its center of gravity center is 6.2m below the center of buoyancy.
3) The maximum stress occurs at the four corners of the top frame. The joints need to be strengthened to avoid local buckling.

4) Motion RAOs of the MV-FSFFC by WAMIT show that the proposed MV-FSFFC concept has better seakeeping performance than the well-know OC3Hywind and OC4DeepCwind concepts.
5) The mooring responses of MV-FSFFC with intact/line-broken mooring systems are also investigated. All safety factors of mooring lines meet the requirement in API-RP 2SK, indicating that the taut mooring system is a feasible mooring for MV-FSFFC to survive design waves.
6) The hydrodynamic analyses by OcraFlex demonstrate that fully coupled time-domain analysis with stochastic waves should be used to precisely capture the responses of a newly developed concept. Regular waves would lead to underestimations.

In addition, aforementioned the VAWT itself carries numerous merits when compared to the VAWT, such as lower gravity center, much lower installation and maintenance costs, smaller neighboring proximity and so on. Therefore, the proposed MV-FSFFC concept will become a competitive and promising design for offshore fish farming and power industries. The concept would be further studied to more precisely examine the effects of wind loads and joint wind-wave action.

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